Development and Testing of an In-well Point Velocity Probe for Preliminary Site Characterization

By

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Development and Testing of an In-well Point Velocity Probe for Rapid Preliminary Site Characterization

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Abstract

The in-well point velocity probe (IWPVP) is a novel device for the centimeter-scale measurement of groundwater velocity within the screened interval of a monitoring well. IWPVP measurements are based on the detection of a tracer pulse that is injected into a central mixing chamber and carried over a detector as groundwater passes through the well and the probe. The viability of the IWPVP design was confirmed by numerical modeling followed by a series of laboratory tank experiments. Initial laboratory tank tests showed the IWPVP design to be viable, measuring groundwater velocity within ±6%, on average, regardless of the orientation of the probe within the well screen, when velocities in the tank ranged between 48 cm/day and 400 cm/day. Following the initial laboratory tank experiments, a new IWPVP was designed with a packing system that permitted easy deployment in the field. Through a second round of laboratory testing, the new IWPVP design was shown to perform nearly identical to the original IWPVP design. Initial field testing of the IWPVP was carried out in an alluvial sand and gravel aquifer at the O'Rourke Bridge Site in Pawnee County, Kansas. Field results showed the IWPVP was able to estimate the flow direction correctly, within the limits of the device, and the groundwater velocity within a factor of three compared to a site-averaged Darcy estimate of groundwater velocity. The latter comparison was hampered by the condition of the well in which the tests were performed. Overall, the IWPVP shows promise as a cost-effective technology for the measurement of groundwater velocity within the screened interval of groundwater monitoring wells.

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

Accurate knowledge of groundwater velocity is particularly important for plume characterization, natural attenuation assessment, risk analyses, and for proper design and implementation of effective compliance monitoring and remediation strategies (Kempf *et al.*, 2013; Labaky *et al.*, 2007; Labaky *et al.*, 2009; Verreydt *et al.*, 2015). The mass distribution within a contaminant plume is highly variable, both spatially and temporally, due to aquifer heterogeneity (Guilbeault *et al.*, 2005; Mackay *et al.*, 1985). Guilbeault *et al.* (2005) showed that even within several aquifers with relatively homogeneous hydraulic parameters (i.e., hydraulic conductivity varied less than half an order of magnitude), plumes emanating from dense non-aqueous phase liquid (DNAPL) sources can exhibit concentrations that vary by 2 to 4 orders of magnitude over a vertical distance of 15 to 30 cm. The dominant factor in the transport of a dissolved contaminant is advection (Mackay *et al.*, 1985). Therefore, without a detailed understanding of groundwater velocity at the centimeter-scale, an accurate knowledge of the plume mass-discharge in difficult to obtain and proper design and implementation of a remedial strategy unlikely. Yet, the ability to characterize groundwater velocity at the centimeter-scale has proven to be challenging.

Typically, groundwater velocity is estimated using a one-dimensional Darcy's Law calculation. Details of the limitations of this approach are well known (Devlin and McElwee, 2007; Post and von Asmuth, 2013) and reviewed in Chapter 2 of this thesis. To overcome the limitations, new methods for more direct measurement of groundwater velocity have been developed (Ballard, 1996; Drost *et al.,* 1968; Hatfield *et al.,* 2005; Kearl, 1997; Kerfoot, 1988; Labaky *et al.*, 2007). Unfortunately, the available technologies tend to be costly, labor intensive, may require potentially problematic volumes (~ 1L or more) of tracer to be introduced to the subsurface, and require specialized training to apply. Furthermore, none offer the possibility of characterizing groundwater velocity at the centimeter scale, which can be advantageous in hydrogeological studies involving contaminants. This study is centered on the development and testing of an in-well point velocity probe (IWPVP), a simple, inexpensive, and reusable device for the measurement of groundwater velocity at the centimeter scale.

1.1 Direct Measurement Techniques

Currently, no available technologies are able to actually measure groundwater velocity *directly* (i.e., direct measurement of the movement of water molecules in the subsurface). However, tracers have been utilized to characterize groundwater velocity with great success, circumventing any use of Darcy's Law, which is indisputably an indirect means of estimating groundwater velocity. For this reason, and for simplicity, tracer-based methods are referred to as direct measurement techniques in this thesis.

The earliest direct measurement technique was the natural gradient tracer test (Schlichter, 1905). Natural gradient tracer tests provide average groundwater velocity measurements, usually over site areas of 100 m^2 or more, by tracking the progress of a tracer through the aquifer and monitoring the tracer's arrival at discrete sampling locations (LeBlanc *et al.*, 1991; Mackay *et al.*, 1986). Although natural gradient tracer tests provide helpful information about the average velocity between the injection and monitoring wells, they tend to be excessively time consuming and labor intensive. Over time, new technologies have been introduced to derive measurements of groundwater velocity at more defined local-scales, frequently using single monitoring wells to access the aquifer.

1.2 Single-well Direct Measurement Techniques

The first single-well groundwater velocity measurement technique developed was the borehole point dilution method (Drost *et al.*, 1968). Borehole point dilution techniques are based on the loss of tracer mass from the screened interval of a well as a function of the horizontal component of groundwater flow through the well. Despite its ability to measure groundwater speed, the borehole point dilution technique provides no information about the direction of flow. This method also depends on time-series chemical sampling, as well as an accurate knowledge of the aquifer porosity to arrive at a reliable estimate of groundwater speed (Kempf *et al.*, 2013).

Within the last three decades, several varieties of borehole flowmeters have been developed and used to measure groundwater flow in wellbores. These include: heat-pulse flowmeters (Hess, 1986; Kerfoot, 1988; Kerfoot and Massard, 1985; Wilson *et al.*, 2001), the colloidal borescope (Kearl, 1997), the acoustic Doppler velocimeters (Momii *et al.* 1993; Wilson *et al.*, 2001), and the passive flux meter (Annable *et al.*, 2005; Hatfield *et al.,* 2005; Klammer *et al.*, 2007; Verreydt *et al.*, 2015). Because all of these flowmeters operate within a wellbore, the technologies all depend on an understanding of the differences between groundwater flow in the wellbore and that in the surrounding aquifer. In theory, the water flux within a wellbore increases relative to that in the aquifer matrix due to the increased hydraulic conductivity in the wellbore. In practice, differences also depend on variations in well construction, well geometry, well development, and the condition of the well screen at the time of measurement. To gain a better understanding of these factors, flow within a wellbore has been the subject of many studies (Bidaux and Tsang, 1991; Drost *et al.*, 1968; Kerfoot, 1988; Kerfoot, 1994; Kerfoot and Massard, 1985; Milne-Thompson, 1968; Wheatcraft and Winterberg, 1985; Wu *et al.*, 2008). Despite the breadth of this research, notable uncertainty still accompanies velocity measurements made in wells. Thus in-well velocity measurements methods are presently best used for preliminary assessment purposes (Bayless *et al.*, 2011; Kearl, 1997).

1.3 *In-Situ* Direct Measurement Techniques

Due to the high degree of measurement uncertainty associated with in-well direct measurement techniques (Bayless *et al.*, 2011; Kempf *et al.*, 2013), techniques for the direct measurement of groundwater velocity have been developed for use without a well. Such direct measurement techniques include: the point velocity probe (Labaky *et al.* 2007; Labaky *et al.*, 2009), the *in-situ* permeable flow sensor (Ballard, 1996), and more recently the groundwater variability probe (Crawford and Chang, 2016). Although all of these techniques have shown great promise, for the purposes of this thesis the point velocity probe is the primary focus.

1.3.1 Point Velocity Probe

The point velocity probe (PVP), was recently developed to directly measure groundwater velocity on the centimeter scale (Labaky *et al.,* 2007; Labaky *et al.*, 2009). PVPs operate by tracking tracer movement on the perimeter of a cylinder. Based on the theory of ideal flow around a smooth cylinder, the apparent velocity at any point on the perimeter of the cylinder is directly related to the average linear velocity unaffected by the presence of the cylinder by the equation (Bird *et al.*, 1960):

$$|v(\theta)| = 2v_\infty \sin\theta \tag{1.1}$$

Where v(θ) is a point velocity along the perimeter of the cylinder, v_∞ is the average linear velocity, and θ is the angle formed by the average linear flow direction and the point at which v is calculated (Figure 1.1). This equation was developed for use in open water environments and does not consider the effects of viscosity or friction between the fluid and solid boundaries. Equation (1.1) is applicable for all values of θ except 0 and 180°, which are points where v(θ) is equal to zero.

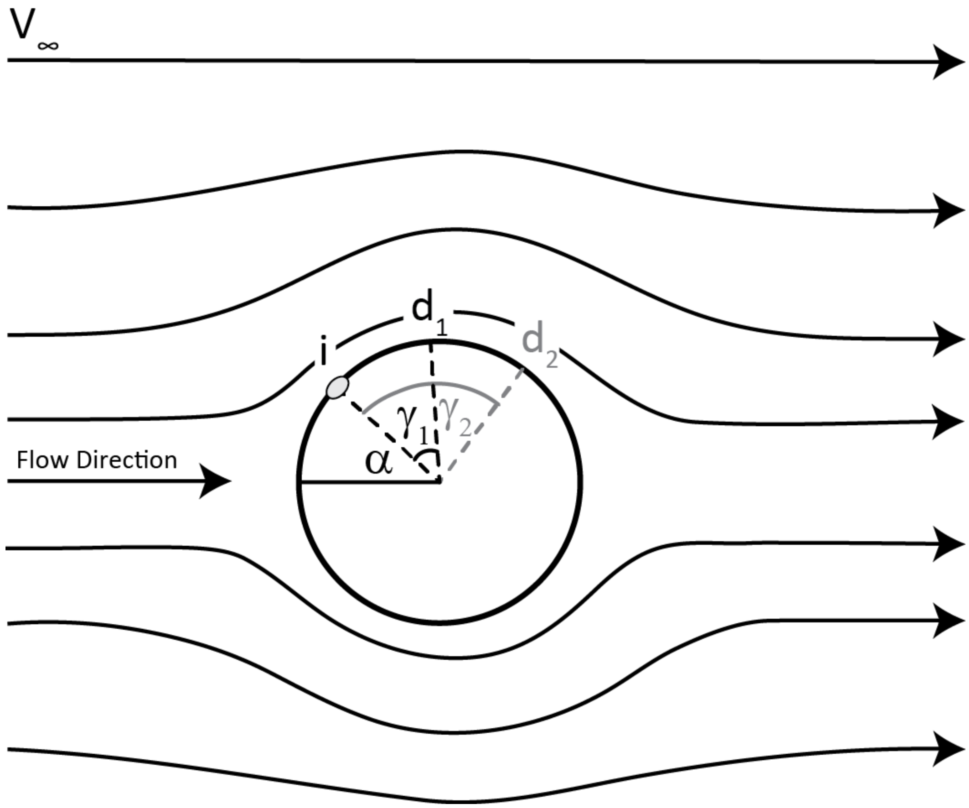

Figure 1.1. Plan view schematic of a point velocity probe consisting of one injection port, i, and two detection pairs, d_1 and d_2, used to measure the groundwater velocity (after Labaky *et al.*, 2007). Note that θ is equal to α plus γ_1 or γ_2 depending on the point at which *v* is calculated.

Assuming equation (1.2) applies to porous media, with two or more detectors on the probe, both the magnitude and direction of groundwater flow velocity can be estimated by the equations:

$$\alpha = \tan^{-1}\left[\frac{v_{app1} * \gamma_1(\cos\gamma_2 - 1) + v_{app2}\gamma_2(1 - \cos\gamma_1)}{v_{app1}\gamma_1 \sin\gamma_2 - v_{app2}\gamma_2 \sin\gamma_1}\right] \quad (1.2)$$

$$v_\infty = \frac{v_{app} * \gamma}{2[\cos\alpha - \cos(\alpha - \gamma)]} \quad (1.3)$$

where v_{app} is the apparent velocity of the tracer measured at a detector on the probe surface, α is the angle formed by the flow direction and the injection port, and γ is the angle between the injection port and the detector (subscripts 1 and 2 refers to the detectors, see Figure 1.1) (See Labaky *et al.*, 2007 for development and alternate equations). It is important to recognize that v_∞ is directly dependent on α, which is a function of both γ_1 and γ_2. Therefore two detectors are required to estimate v_∞ when the flow direction is unknown, despite the use of a singular detector pair in equation 1.4 (Labaky *et al.*, 2007).

When a small volume of tracer is injected into the flow system through an injection port, the tracer pulse is carried around the surface of the cylinder and detectors. Breakthrough curves (BTCs) are recorded as the tracer passes each detector, creating a change in electrical conductivity between each detector pair. Apparent velocities can be generated by fitting the BTCs to a solution of the advection-dispersion equation (ADE). The data analysis process has recently been expedited with the development of VelProbePE, a Visual Basic for Applications (VBA) program within an Excel spreadsheet environment. VelProbePE is used to import and process initial data, generate a best-fit solution of a 1-D ADE based on the observed BTCs, and to convert the apparent velocities to the ambient groundwater velocity (Schillig, 2012).

Unlike methods that depend on wells to access the subsurface, PVPs are installed in direct contact with the aquifer material and therefore do not require a well. Furthermore, PVPs do not require calibration as most in-well methods do. In addition, PVPs are inexpensive to manufacture, can provide multiple measurements over time once installed, can measure groundwater velocity within the capillary fringe, can be used to determine whether or not biostimulation causes flow variations, and can be stacked into an array providing information about vertical variations of groundwater velocities throughout designated aquifer zones (Berg and Gillham, 2010; Devlin, *et al.* 2009; Devlin *et al.*, 2011, Schillig *et al.*, 2011; Schillig *et al.*, 2016). Yet, the upfront cost associated with PVP installation has proven to be a barrier for the technology to gain widespread acceptance. In order to overcome this barrier, a less costly version of the PVP, deployable in wells and capable of providing preliminary velocity estimations, could be of great value. Such a device would collect similar tracer-based data, use the same hardware to collect and store the data, and the same software to analyze the data as the original PVPs. The major difference being the way in which the measured apparent velocities are used to calculate the average linear groundwater velocity. In this way, sites in need of higher quality velocity estimates may be identified at low cost, and personnel training can be minimized going between the two PVP probe types.

1.4 Early work leading to this study

Initial design and testing of a point velocity probe for in-well use was completed by J.F. Devlin and R. Firdous. The basic difference between the theory presented above and the theory used for the development of the IWPVP is that the IWPVP is designed to conduct a mini-tracer test inside the probe and without the presence of a porous medium. Preliminary IWPVP designs utilized a quadrant funnel and gate system which captured water as it flowed into the well screen. The funnel design then directed water through the body of the probe (i.e. through the channels) (**Error! Reference source not found.**). Each channel housed one pair of detector wires designed to detect a tracer pulse introduced in the center of the probe, producing a breakthrough curve. The tracer breakthrough curve can be used to quantify groundwater velocity by fitting it to a solution of the advection-dispersion equation, as described by Devlin (1994), and Schillig (2012).

The initial IWPVP design was printed using a 3-D printer with the injection line and detector wires assembled by hand. Design testing of the early IWPVPs was conducted using a hand-cut well screen (**Error! Reference source not found.**) installed in a sandbox aquifer simulator constructed from nested storage tanks as described

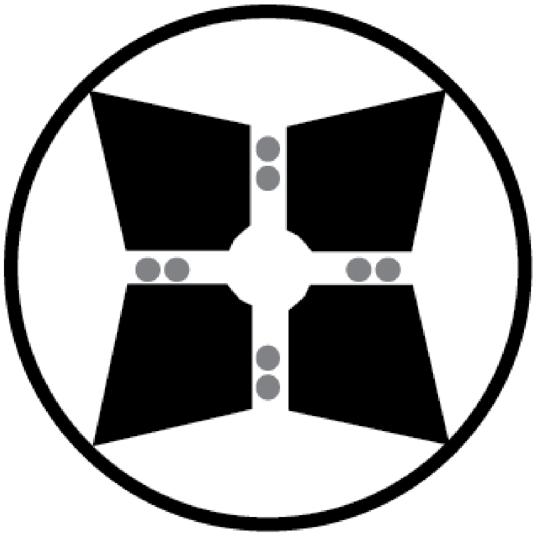

***Figure 1.2**. Plan view schematic of the IWPVP illustrating the quadrant funnel and gate system, solid black polygons, and the detector pairs, solid gray circles, within each channel.*

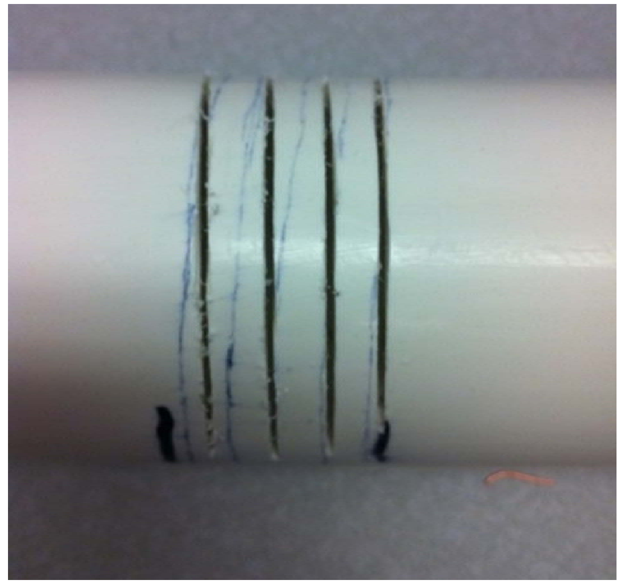

***Figure 1.3**.* Initial hand-cut well screen comprised of four 3mm wide slots spaced at a 1 cm interval.

by Bowen *et al.*, 2012. Preliminary results showed, at best, the device produced a linear calibration response for groundwater velocities between approximately 168 and 272 cm/day, with increasing scatter as aquifer velocities increased (Figure 1.4).

The initial benchtop testing indicated that the IWPVP had sufficient potential to warrant further testing and development. Specifically, further work was needed in several areas: first, this initial work only showed that the IWPVP was able to measure velocity over a limited range of groundwater velocities; extended ranges of velocity have to be tested to include the typical range of groundwater velocities observed in the field, 1 m/year to 1000 m/year (Mackay *et al.*, 1985). Second, the reproducibility of measurements from the device was insufficient, so design alterations and methodology had to be optimized to improve reproducibility. Third, the initial design did not promote efficient mixing of the salt solution used as a tracer, leading to the measurements being affected by density induced flow. Lastly, the initial design was only subject to testing within a hand-cut well screen, therefore the probes' ability to measure groundwater velocity within commercially available well screens was unknown.

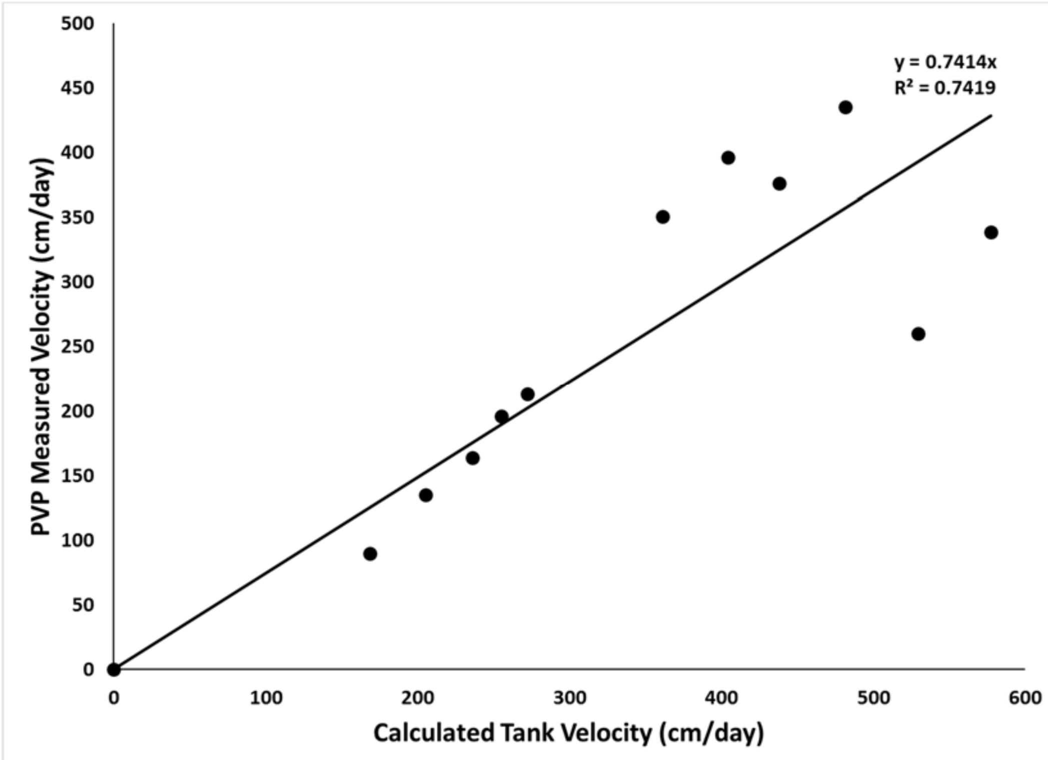

Figure 1.4. Initial IWPVP results from sand tank testing. Note the linear trend when tank velocities ranged from 168 cm/day to 272 cm/day, and the increased scatter produced with increased tank velocities.

1.5 Statement of Objectives

The objective of this study is to further investigate the preliminary design and test a simple, inexpensive, and reusable device based on the theory of the traditional PVP for the measurement of groundwater velocities at the centimeter scale within groundwater wells.

For the purposes of this thesis, the objective was subdivided into two sets of goals:

1. Validate conceptual theory behind the IWPVP design and test the ability of the original IWPVP design to measure horizontal groundwater velocity within the screened portion of a well.

   a. Construct a 2-D numerical model to (1) determine the viability of the IWPVP design, (2) establish a conceptual model of the system, (3) assist in design optimization, and (4) provide a tool for the understanding of experimental results.
   b. Perform as series of highly controlled laboratory experiments to (1) examine the measurement reproducibility of the IWPVP to determine measurement uncertainty, (2) extend the velocity range over which the IWPVP operates to incorporate a larger range of groundwater velocities commonly observed in the field, (3) examine the sensitivity of the IWPVP to various commercial well screens and measurement orientations, and (4) examine the sensitivity of the IWPVP to the condition of the porous media of the surrounding aquifer.
2. Design, laboratory test, and field test an IWPVP with a brush packer system capable of isolating the measurement interval and that promotes easy deployment, rotation and recovery.
   a. Modify the prototype IWPVP design to accommodate the brush packer system.
   b. Perform a series of laboratory tests to determine (1) the viability of the brush packer system through a series of laboratory tests, and (2) the easy of deployment, rotation and recovery of the new IWPVP design.
   c. Field test the IWPVP to determine the tool's ability to measure groundwater velocity under non-idealized conditions.

The first set of goals are addressed in Chapter 2.0 and the second set of goals are addressed in Chapter 3.0. The thesis chapters have been prepared in manuscript format and therefore contain background information that may seem redundant but is necessary for the stand-alone nature of the manuscripts.

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2.0 Design and Laboratory Testing of an In-well Point Velocity Probe

2.1 Abstract

A novel device, the in-well point velocity probe (IWPVP), was designed to be an inexpensive tool for obtaining rapid, preliminary measurements of groundwater velocity at the centimeter-scale within the screened portion of a well. IWPVP measurements are based on the detection of a tracer pulse that is injected into the center of the probe and carried over a detector as groundwater passes through the well. The viability of the IWPVP design was confirmed by numerical modeling that accounted for laminar flow in the porous medium outside the well and turbulent flow inside the well (and probe), followed by a series of laboratory tank experiments in which the probe was calibrated to flow in a medium sand. The magnitude of the groundwater velocity in the sand tank was determined within ± 6%, on average, when simulated groundwater velocities in the tank were between 48 and 400 cm/day. Tests could be completed in less than 20 minutes in all cases. The design of the IWPVP permits the determination of horizontal flow directions within a 90° arc. Based on these encouraging early findings, the IWPVP appears to be a viable tool for verification of small-scale groundwater velocity.

2.2 Introduction

Groundwater velocity is of primary concern for the movement of solutes in aquifers. Sudicky (1986) showed that aquifer heterogeneity of significance to transport processes exist even in geologically simple aquifers, such as the C.F.B. Borden aquifer. Thus, small-scale variations in groundwater velocity should be expected in aquifers, with corresponding variations imposed on the groundwater flow regime. Without a detailed understanding of groundwater velocity variations in an aquifer, natural attenuation assessment, risk analyses, effective compliance monitoring and remediation design cannot be completed with the highest confidence (Kempf *et al.,* 2013; Labaky *et al.,* 2007; Labaky *et al.*, 2009; Verreydt *et al.,* 2015). The effect of such small-scale variations in groundwater velocity has been demonstrated in field experiments (Gierczak *et al.,* 2006; Schillig *et al.,* 2011; Schillig *et al.,* 2016).

Traditionally, groundwater velocity is estimated by calculating the specific discharge, q (L/T), corrected for porosity, n (dimensionless), using Darcy's Law,

$$v = \frac{q}{n} - \frac{K}{n}\frac{\Delta H}{\Delta x} \tag{2.1}$$

where *v* is the average linear groundwater velocity (L/T), *K* is the hydraulic conductivity (L/T), *ΔH* is the change in hydraulic head (L) over the distance *Δx* in the direction of flow (L) (units are generalized where L is length and T is time). The directional component of the velocity vector is commonly obtained assuming an isotropic aquifer with flow occurring perpendicular to contoured equipotential lines.

Despite the wide acceptance and usage of the Darcy's Law approach to estimate velocity, it is well known that the method is associated with potentially large sources of error connected with parameter identification and issues of scale. The primary source of parameter error in Darcy-based calculations stems from estimates of *K,* which can vary over 13 orders of magnitude in natural deposits (Freeze and Cherry, 1979). Variations in *K* as much as 2 orders of magnitude were reported in the Borden aquifer (Sudicky, 1986), which Mackay *et al.* (1986, pg. 2019) referred to as being comprised of clean, well-sorted, fine- to medium-grained sand that is "quite homogeneous relative to many aquifers of similar origin". The high variability in *K* arises from bedding features that place sediments with contrasting permeabilities within millimeter to centimeter distances of one another. Although efforts have been made to improve the quality of estimated *K* values, detailed measurements of hydraulic conductivity by such methods as high-resolution slug testing, do not resolve the issue completely. In addition, hydraulic gradient measurements are subject to important errors (Post and von Asmuth, 2013). For example, when measuring the hydraulic gradient, a large distance between monitoring wells may be needed in order to obtain a measurable difference in hydraulic heads, particularly in highly permeable sediments (Devlin and McElwee, 2007). The scale over which a gradient can be measured may not be representative of the desired velocity measurement, or may not even be achievable at small sites.

With these considerations in mind, it is clear that Darcy-based ('conventional') methods for estimating groundwater velocity are not well suited for all cases – especially for cases where centimeter- to meter-scale variations may be important. An alternative to Darcy-based calculations is the use of a 'direct' velocity measurement technique. There is no technology that is currently able to truly measure water velocity directly, but the use of tracers to characterize water velocity has been used with great success in the past and circumvents the use of Darcy's Law. As alluded to in the first chapter of this thesis, the tracer-based methods are referred to as direct velocity measurements. Several such methods have been developed and utilized in hydrogeological studies over the past century, beginning with natural gradient tracer tests (NGTT) (Schilichter, 1905), and continuing with the point dilution method (reviewed and summarized by Drost *et al.,* 1968), the heat-pulse flowmeter (Kerfoot, 1988),the colloidal borescope (Kearl, 1997), the acoustic Doppler flowmeter (Wilson *et al.,* 2001), and the passive flux meter (Hatfield *et al.,* 2004), which are all discussed in more detail in Chapter 1. With the exception of the NGTTs, all the aforementioned technologies are single-well technologies. These have the advantages of potential cost savings over NGTTs, since spatial variability can be assessed across a site with one or two probes, and that pre-existing piezometers may be utilized to deploy the devices.

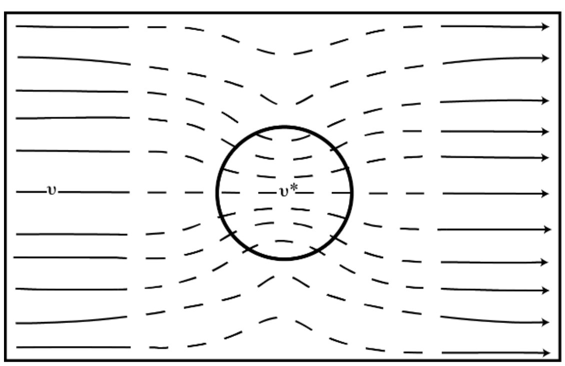
A small number of technologies that permit direct measurement of groundwater velocity using probes in direct contact with the formation also exist (i.e., no wells or screens are used). The point velocity probe (PVP), introduced in Chapter 1, is an example of a direct measurement technique that does not require a well, and is suitable for use in unconsolidated, noncohesive, porous media. A PVP can be deployed singly or in multilevel stands, and sampled repeatedly over time (Devlin *et al.,* 2009; Devlin *et al.*, 2011). The probes can be constructed by hand from readily available, inexpensive materials (Devlin *et al.,* 2009). The disadvantages of PVPs are that they are not suitable for use in cohesive, fine-grained sediments such as silt and clay, or consolidated materials such as rock. Also, PVPs require dedicated boreholes and these tend to dominate the cost of installation.

The purpose of this work was to develop and test a simple, inexpensive, reusable tool for centimeter-scale *in-situ* measurements of groundwater velocity within the screened interval of groundwater monitoring wells. The latter requirement makes the tool subject to limitations common to most in-well technologies, such as the need for calibration, and the uncertainties that come with measurements affected by well screens. However, the introduction of such a tool makes it possible and affordable to quickly gather data for rapid preliminary site investigations, or preliminary verification of conceptual flow models based on Darcy-derived estimates of groundwater velocities, and other site characterization techniques. A further objective for the tool is that it be suitable for high-resolution investigations – with a resolution of about 5 cm – making it potentially useful for identifying preferential flow paths that intersect the well screen.

2.3 Materials and Methods

2.3.1 Probe Concept

a)



b)

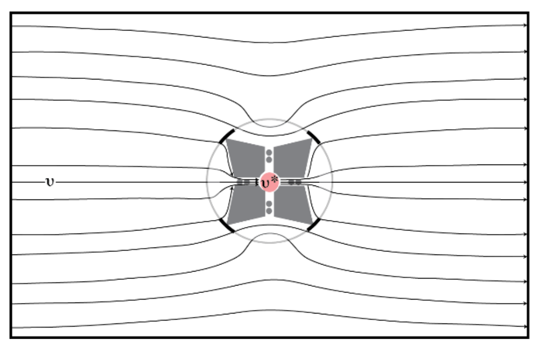


Figure 2.1. Plan view schematics of flow distortion caused by well bores. (a) The distortion of flow caused by the presence of an open well screen (Modified from Freeze and Cherry, 1979). (b) The distortion of flow caused by the presence of a well screen captured by the funnel and gate, quadrant design of the IWPVP consisting of an injection port in the center of the probe, red circle, and detector pairs in the channel of each funnel, gray circles.

It is well known that with the installation of a groundwater monitoring well comes an area of flow disturbance next to the well (**Error! Reference source not found.**) (Drost *et al*, 1968; Freeze and Cherry, 1979). Beyond the zone of disturbance, the average linear velocity, v_∞, applies. Within the well, an average bulk velocity, v^*_{well}, differs from v_∞. A probe was designed that captures the flow entering the upgradient side of the well, and focuses it through a detection system. Along the way, a tracer, released into the central chamber of the probe, is carried across the down-stream detector, giving information about the magnitude and general flow direction (Figure 2.1). In this work, the detection system consists of stainless steel wires passing through channels in the probe. Changes in electrical conductivity of the groundwater – due to the passage of the tracer through the probe – are measured as voltage changes across the wires of the detectors. These signals can be converted into the breakthrough curves (BTC) of the tracer. Average bulk velocity of water inside the probe, v^*_{probe}, is calculated from the BTCs with Excel-based free software, VelProbePE (Schillig, 2012), using two different methods: (a) fitting of a 1-D advection – dispersion equation and (b) 1-D method of moments calculation, modified from Freyberg (1986).

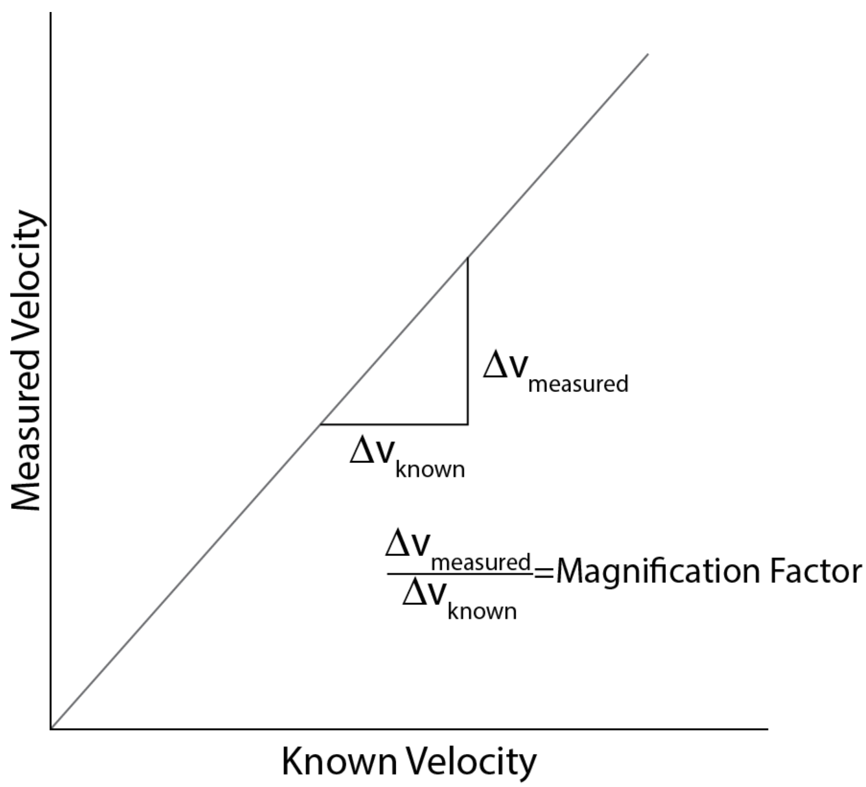


Figure 2.2. Schematic of a theoretical calibration line illustrating how the slope of the line is used to quantify the magnification of flow velocity within the well screen.

Because the speed of the water in the probe is proportional to the ambient groundwater velocity beyond the influence of the well, a calibration line can be plotted to relate the two quantities (Figure 2.2). Calibration lines depend on properties of the aquifer medium and the well construction, so site-specific calibration lines are likely to be required for best results. Once a field measurement of groundwater velocity is made, the magnitude of the average linear velocity vector in the aquifer can be estimated from the calibration line. The directional component of the velocity vector can also be estimated based on the orientation of the probe within the well screen and the relative proportions of tracer mass leaving the probe through the four channels. Although best-estimates of flow direction can be calculated as vector additions of the flow components from each channel, the uncertainties associated with the well screen's effects on flow are likely to limit the accuracy of estimated directions in many cases.

2.3.2 Experimental Methods

To assess the viability of a groundwater velocity probe based on the above approach, a prototype probe was constructed on a 3D printer and subjected to laboratory testing. The IWPVP prototype was designed using Trimble SketchUp®, and printed with ABS (Acrylonitrile Butadiene Styrene) plastic. The initial IWPVP was designed for use in 6.35 cm outside diameter (O.D.) well screens with an O.D. of 5.1 cm and a height of 5 cm (**Error! Reference source not found.**). The basic probe design consisted of four funnels that guided water through four channels into a central chamber. The channels housed the tracer detectors, and the chamber served as the tracer introduction point in the probe.

The detection system was designed to sense changes in the conductance of water passing through the probe. It was manually assembled using 30 pound test stainless steel fishing lead (wire). A single detector consisted of a pair of wires located inside each of the four channels of the probe. The detector wires were connected to a Campbell Scientific CR1000 data logger that recorded the resistivity of the water around the detector wire at a 1 second interval. The distance between the injection point (assumed the center of the central chamber), and the detector wire furthest away from the chamber in the active channel (1.06 cm in each channel) was used as the travel distance in the velocity calculations. It is important to recognize due to the half-bridge structure of the detector pair circuit, the tracer must be present at each individual wire of the detector pair for a signal to be generated. Therefore, the travel distance will always be to the detector wire furthest from the injection point

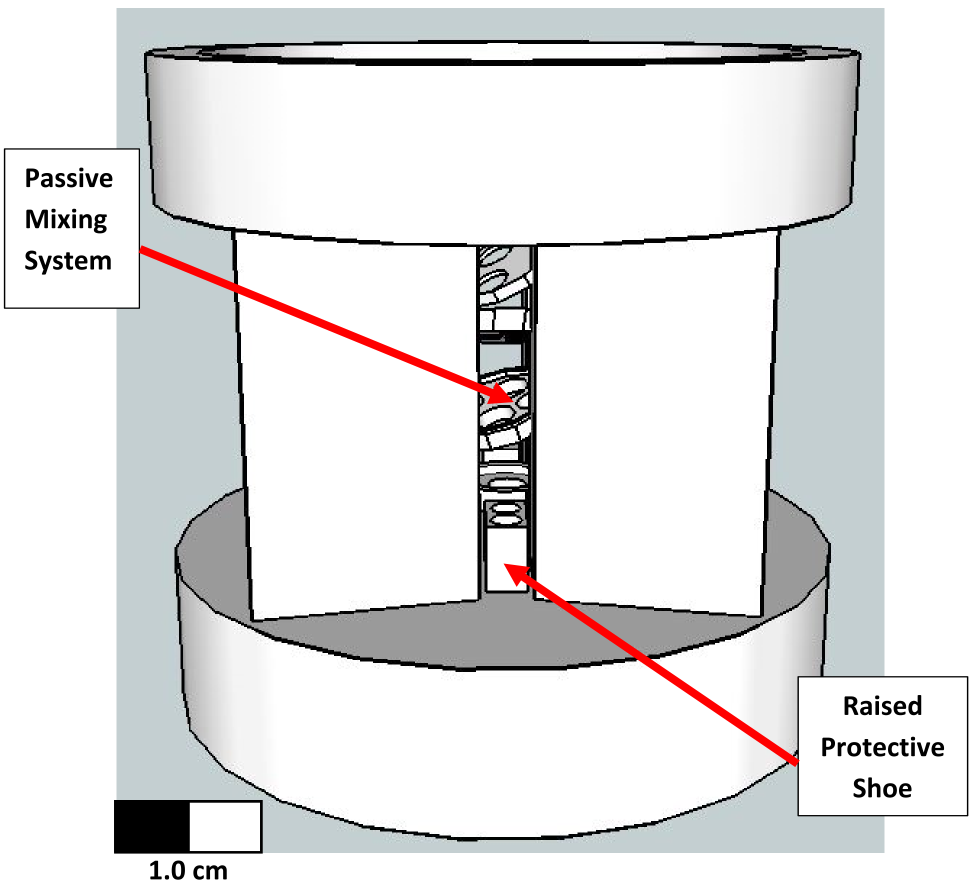


***Figure 2.3**.* SketchUp schematic of the IWPVP design illustrating the central passive mixing system and the raised protective shoes.

For experimental testing, the probe was installed in a well screen to establish a measurement interval that was isolated by friction fitting the probe against the inside wall of the well screen. Flow around funnels outside the probe (but inside the well) was eliminated with additional friction fits using weather stripping.

To initiate a test, a small volume of saline tracer solution (0.1 to 0.5 mL) was injected into the top of the central chamber. Because IWPVP measurements are based on the movement of a salt solution tracer in the open water of the well and the probe, the system is sensitive to density gradients and care must be exercised to ensure that the measured velocity is not due to density driven flow. Therefore, a passive mixing system was designed to mix the tracer solution with ambient groundwater in the central chamber to maximize the tracer mass carried into the detector channels by flowing groundwater, and to minimize tracer loss due to density flow. Excess tracer solution that sank to the bottom of the central chamber passed out of the probe without contacting the detector wires, which were protected by the raised shoes at the bases of the channels.

The apparatus to control the injections consisted of a t-connector linking a 60 mL syringe and a 1 mL syringe both filled with the salt tracer solution. An automated syringe pump was used to deliver the small volumes of tracer (0.1mL) in each experiment. The use of the automated injection system ensured all injections were conducted identically.

All tests were performed in a sandbox aquifer simulator (35.5 cm wide, 54 cm long, and 30 cm deep), constructed from nested storage tanks (NeST) as described by Bowen *et al.* (2012). The central compartment was filled with homogeneous medium-grained sand packed to a porosity of approximately 0.33.

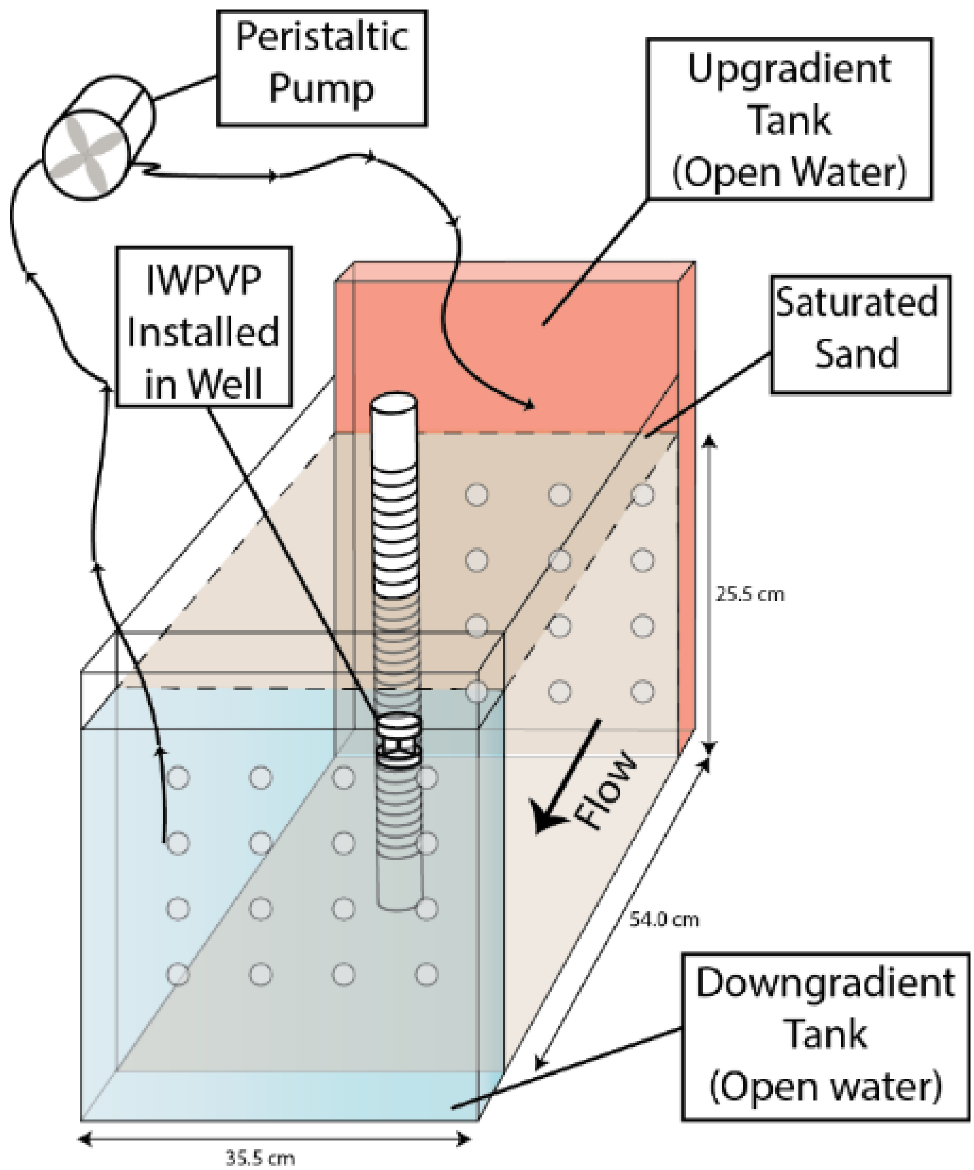


Figure 2.4. Schematic of the NeST experimental apparatus used to asses IWPVP performance.

All experiments in this study were conducted using a schedule 40 PVC, 0.508 mm (0.020 in) slot width, 4 slot commercial well screen.

An empty well screen was placed in the center of the sand-packed tank, in direct contact with the sand (no filter pack) with screen openings oriented upgradient. The tank was then filled with water and sand was packed around the well screen to a total depth of 25.5 cm (**Error! Reference source not found.**). Once the sand was packed around the screen a smaller diameter PVC pipe was used to surge the well a minimum of 6 times, to ensure a good hydraulic connection with the porous medium. After screen development, the probe was oriented with a selected funnel opening pointing upgradient and then pushed down to the final installation depth. The pump was then turned on for a minimum of 2 hours before testing began, to allow the flow in the tank to stabilize.

Experimental testing of the influences of tracer strength, injection volume, and injection length were conducted. These tests showed little sensitivity in the accuracy or precision of measured velocities when tracer strength varied between 0.25 g/l and 0.5 g/l NaCl, or when injection times varied from 5 to 30 seconds. On this basis, for the bulk of the tests performed, the tracer injections were set to 0.10 mL pulses, administered over a period of ten seconds, using a 250 mg/L NaCl solution. Data were recorded by a Campbell Scientific CR1000 data logger at a 1 second interval.

The average expected flow velocity in the sandbox, based on the recirculation rate of water through the tank, was determined by a one-minute pumping rate test before and after every IWPVP measurement, and the following equation:

$$v = \frac{Q}{A * n} \tag{2.2}$$

where *Q* is the pump discharge (cm^3/min), *A* is the cross-section area of the sandbox (cm^2), and *n* is the porosity (dimensionless). After each pumping rate test was completed, a minimum of five minutes was allowed for the flow rate through the sand to re-equilibrate before another measurement was initiated, to avoid possible interference between tests. Water collected during pumping rate tests was collected in a 2L graduated cylinder and held there until all experiments were completed at that pumping rate. It was then reintroduced to the upstream tank reservoir and the pumping rate set to the next level. This then began a period of flow stabilization that lasted at least 45 minutes. Four replicate measurements of each test were made to determine the measurement precision.

2.3.3 Numerical Simulations

A 2-D steady-state numerical model of a probe inside a well that was emplaced in a porous medium was created using the free and porous media flow packages in COMSOL Multiphysics (www.COMSOL.com). Due to the 2-D nature of the model, the simulations represented a slice through the center of a well. Therefore, the model did not account for flow resistance arising from the slotted nature of the well screen (i.e., alternating open and closed segments).

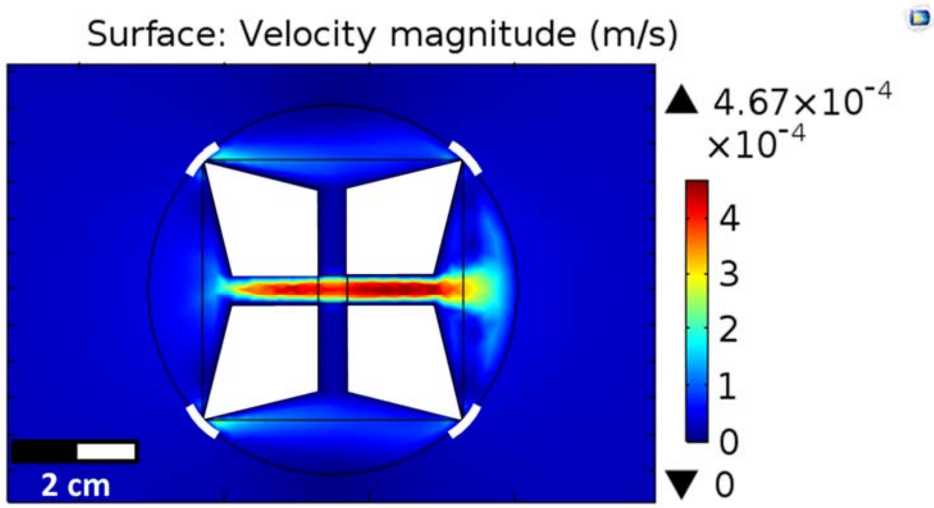


Figure 2.5. Color flood of simulated velocities when the constant velocity boundary was set to 200 cm/day, returning an IWPVP measured velocity of 3844 cm/day. The IWPVP and solid portions of the well screen are overlain in white for visualization. Note, this figure shows only the well screen with the IWPVP to illustrate the velocity magnification within the IWPVP. The remainder of the simulated porous media, not pictured, returned uniform simulated velocities equal to the constant input velocity for all numerical simulations.

The porous medium tank was modeled as a 25.5 cm by 54 cm rectangle with the properties of homogeneous sand (COMSOL input: permeability = $1e^{-7}$ cm^2 (≈10 darcy), and porosity = 0.33), and a 6.35 cm O.D. circle containing open water, representing the well. Within the circle of open water, the probe was simulated as symmetrically arranged solid blocks with zero permeability (**Error! Reference source not found.**). The simulations yielded velocity estimates from the flow calculations; no transport simulations were undertaken. The left boundary of the domain was defined as a constant velocity boundary. The right boundary was defined as a free exit boundary. The boundaries running parallel to the flow direction were defined as no flow boundaries (**Error! Reference source not found.**).

2.4 Results and Discussion

2.4.1 Numerical modeling

The theoretical viability of the probe design was demonstrated by simulating the probe numerically in a flow system. Several simulations were performed to examine the effect of flow magnitude and screen type on velocities measured by the probe. Since the probe operates in open water, there were some questions concerning the effects of turbulence on the linearity of the probe response. An important finding of these simulations was that the water velocities measured in the probe were considerably greater than those expected in the surrounding porous medium. Specifically, for values of v_{∞} of 48 cm/day to 400 cm/day, the velocities in the modeled probe, v^{*}_{probe}, were found to range from about 1000 cm/day to 8500 cm/day, respectively. The correlation between these sets of velocities was found to be linear with a slope of 18.6 (**Error! Reference source not found.**).

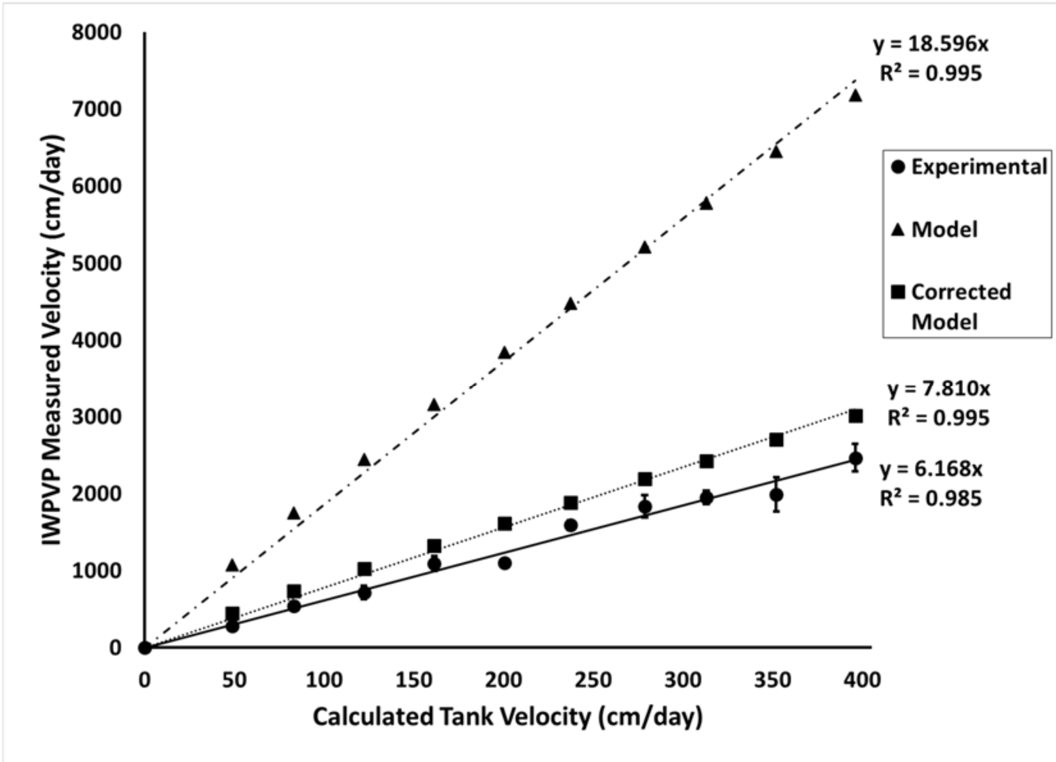


***Figure 2.6**.* Comparison of the experimental (circles) and model (triangles) calibration lines. The model calibration line shows a clear positive bias compared to the experimental line, due to the inability of the model to incorporate well-screen resistance. Once the model has been corrected using a 58% resistance factor, the experimental (circles) and corrected model (squares) calibration lines show strong agreement.

2.4.2 Measurement of Horizontal Velocities

Experimental evaluation of the IWPVP was undertaken with a series of laboratory tank experiments. Duplicating the conditions represented in the numerical modeling exercise as closely as possible, tests were performed with velocities in the sand tank between 48 and 400 cm/day. The test wells were constructed with a #20 commercial well screen comprising 4 rows of slots. The precision of the probe measurements was assessed by repeating the tests in quadruplicate and examining the spread of the results. The laboratory experiments were found to be repeatable within ± 7%, on average (**Error! Reference source not found.**).

The accuracy of the probe was ensured with an experimental calibration line to match the modeled line (**Error! Reference source not found.**). Experimentally, the 4-row screen was found to produce a linear calibration line with a slope of 6.2, notably less than predicted by the model. This result was expected in a qualitative sense since the numerical simulations did not account for the resistance to flow imposed by the well screens. To account for that difference, the work of Kerfoot and Massard (1985) was consulted. They found that commercial well screens could be quantitatively assigned resistance factors to account for screen construction and the proportion of surface area through which water could not pass. Among the screens tested was a #20 4-row screen, similar to the well screen utilized in the current experiments. The resistance factor reported for that screen was 58%. This factor applies to an ideal screen in a well-controlled laboratory experiment and may not be applicable, generally, to screens in field settings. However, for purposes of comparing the model with our controlled experiments the factor should be appropriate. Correcting the flow rates predicted by the model downward by 58% resulted in a calibration line that compared very favorably to the experimental data, supporting the notion that well screen resistance was the cause of the different slopes (**Error! Reference source not found.**).

The repeatability and the sensitivity of IWPVP velocity measurements to well screen conditions was further investigated by installing the four slot well screen two times in two independently packed tanks. The same installation methods were used in all tests. Altogether, 64 tank experiments were completed in the two separately packed tanks. Over these tests, the slopes of the calibration lines were found to vary ± 17%, on average (**Error! Reference source not found.**). This degree of variability is similar to what was reported for PVP tests conducted in separately-packed tanks (Gibson and Devlin, in preparation), and therefore likely represents variability in the porous medium more than instrument variability. Although ± 17% was found to be the difference in calibration lines here, similar experiments with other sediments could result in higher degrees of uncertainty. Further work is needed to investigate a range of sediment types that might be comparable to field cases. The repeatability of the IWPVP in back-to-back tests demonstrates the ability of IWPVP measurements to be temporally correlated, so long as the conditions of the well screen do not changes drastically between measurements. For the purposes of preliminary field measurements a composite calibration line, consisting of measurements from tanks packed with sediments representative of the field site, could be used.

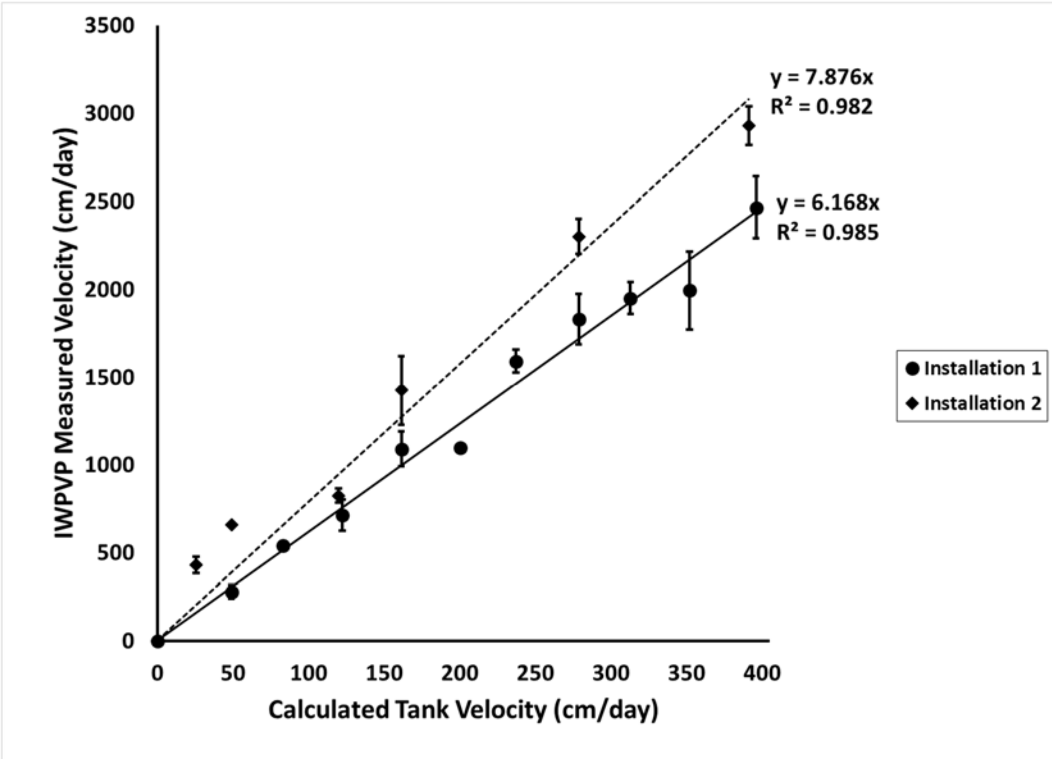


Figure 2.7. Agreement between the experimental calibration lines for the two well-screen installations. The slight difference between the slopes of the calibration lines is thought to be related to differences in well-screen condition and tank packing.

2.4.3 Measurement of Flow direction

An evaluation of the IWPVP flow direction capabilities was examined through a series of tests in which the probe was systematically rotated in the well to represent different incident angles of groundwater flow. These tests were conducted at two tank velocities, 48 cm/day and 166 cm/day. Testing began with the IWPVP oriented to have the channels containing detectors HB4 and HB2 aligned parallel with the flow direction. Between each successive series of four replicate tests, the IWPVP was systematically rotated 10° clockwise within the well screen (**Error! Reference source not found.**). As the probe was rotated, flow was collected by multiple channels, and was discharged similarly. An attempt was made to determine the directional component of groundwater velocity by vector analyses of the measured velocities from the various channels, based on the BTCs from the respective detectors. For example, if only one channel produced a BTC, the groundwater velocity was calculated assuming flow was parallel

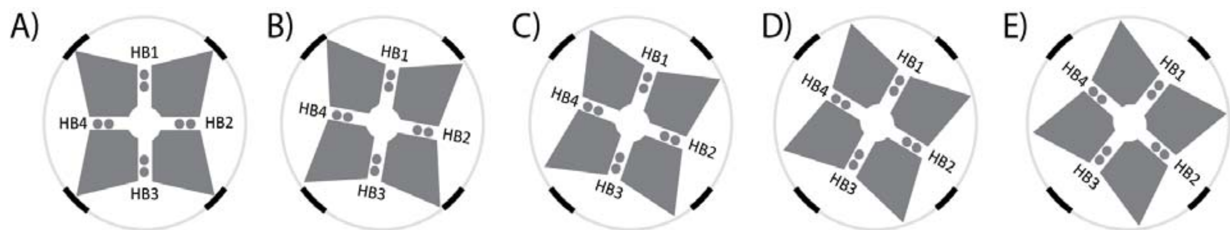


Figure 2.8. Schematic of IWPVP orientations used for the rotation tests 0° - 40°, A through E respectively, with groundwater flowing from left to right.

to that channel. If two channels produced BTCs, the directional component of groundwater velocity was determined from the vector addition of the two responses, leading to a net speed and direction. The magnitude component was then calculated by dividing the magnitude of the resultant vector by 1.4 (**Error! Reference source not found.**). The correction factor of 1.4 was derived based on the geometry of the IWPVPs quadrant design. When two BTCs occur, the resultant vector will indicate flow directly into one of the funnel systems. Basic trigonometry shows that the hypotenuse (resultant vector) of a right triangle with two 45° angles will always be 1.4 times larger than the other sides. Estimations of the true flow direction can be further constrained by comparing the magnitude of the two observed BTCs, although these estimations can only be done in a qualitative sense. In the 40 tests conducted with differently oriented IWPVPs, the magnitude of groundwater velocity was determined within a maximum of ± 13% standard deviation. Well within the standard deviation observed from the repeatability tests above. This result suggests that the probe is capable of reasonably good determinations of flow direction under the most favorable conditions. In field applications, where well screens may not be ideally connected to the aquifer, or suffer some form of damage, flow direction determinations are likely to be less certain.

Table 2.1. Summary of IWPVP rotation testing						
IWPVP Orientation (° clockwise from upgradient)	**Tank Velocity = 51 cm/day**			**Tank Velocity = 166 cm/day**		
	HB2 Velocity	**HB1 Velocity**	**Corrected Resultant Velocity**	**HB2 Velocity**	**HB1 Velocity**	**Corrected Resultant Velocity**
0	423.9	0	423.9	1495.9	0	1495.9
10	437.0	0	437.0	1521.4	0	1521.4
20	433.9	333.1	370.0	1452.2	1264.6	1376.1
30	385.2	385.5	389.7	1706.1	894.2	1377.4
40	473.0	461.4	472.2	1306.7	1418.7	1383.7

2.5 Conclusions

In summary, the laboratory and numerical testing of the IWPVP show that accurate measurements of groundwater velocity are possible with this instrument. The IWPVP returned measurements of groundwater velocity with a maximum standard deviation of ± 14% in idealized laboratory experiments, which appears to be caused by slight differences in tank packing. Based on the initial benchtop testing, the IWPVP appears to be a viable tool for the verification of local-scale groundwater velocity, within ± 30% (roughly twice the experimental uncertainty). To use the IWPVP in the field, care must be taken to maximize the development of the well to ensure good connection with the aquifer. Further, based on the rotation testing, the orientation of the IWPVP within the well screen will not affect the ability to make reliable measurements. On the basis of the consistent results from both the modeling and the laboratory testing under idealized conditions, the IWPVP appears to be an inexpensive tool to obtain groundwater velocity measurements for use in conjunction with, or verification of, more traditional methods of assessing groundwater velocity.

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3.0 Preliminary Field Testing of the In-well Point Velocity Probe

3.1 Abstract

The in-well point velocity probe (IWPVP) is a relatively low-cost reusable instrument capable of measuring groundwater velocity within the screened interval of a monitoring well at the centimeter scale. IWPVP velocity measurements are based on the detection of an electrically conductive tracer as it is transported through the probe by groundwater, which can then be related back to the groundwater velocity within the aquifer. This study presents the design of the field IWPVP with a brush packer system and the results of the initial field testing of the device. The validation of the novel brush packing system was completed through a series of laboratory benchtop testing that indicated the brush packer system performed suitably well for field testing. Initial field testing of the IWPVP was undertaken at a well characterized alluvial aquifer of the Arkansas River in Pawnee County, Kansas. Six IWPVP measurements from one well were compared to a site-wide Darcy-based estimation of groundwater velocity. The IWPVP was able to estimate groundwater velocities within a factor of three when compared to the Darcy-based estimation, with both methods estimating a general direction of flow to be to the southeast. Although the IWPVP estimations of groundwater velocity were bias low, imperfections in the well screen (i.e. lack of development and root mat growth) made assessment of the IWPVP difficult. Overall, the IWPVP appears to be a promising cost-effective tool for the rapid measurement of groundwater velocity within the screened portion of groundwater monitoring wells.

3.2 Introduction

In order to best implement *in-situ* measurement and remediation technologies, reliable estimates of groundwater velocities at local scales are needed. While several techniques for making such measurements are available (Crawford and Chang, 2016; Drost *et al.*, 1968; Hatfield *et al.*, 2004; Kearl, 1997; Kerfoot, 1988; Labaky *et al.*, 2009; Schlichter, 1905; Wilson *et al.*, 2001), groundwater velocity is most often estimated indirectly, using a 1-D Darcy's law calculation (2.1) The groundwater flow direction is commonly obtained from water level data, assuming flow is perpendicular to contoured equipotential lines.

Despite the many advantages of the Darcy's law-based approach to estimate groundwater velocity, Darcy-based calculations are accompanied by potentially large sources of error. The principal source of error is the accuracy of estimated *K*. Additionally, difficulties associated with measuring representative hydraulic gradients have been problematic in some cases (Devlin and McElwee, 2007; Post and von Asmuth, 2013). In one case, a single poorly connected monitoring well was shown to bias gradient calculations strongly affecting calculated flow directions (Schillig *et al.*, 2016). It follows that obtaining field measurements of groundwater velocities in addition to the Darcy-based estimations could be advantageous, especially in cases where subtle errors could be consequential, such as when *in-situ* remediation techniques are at issue.

Recently, a novel device for measuring centimeter-scale groundwater velocity within groundwater monitoring wells was introduced, the in-well point velocity probe (IWPVP). IWPVP measurements are based on a mini-tracer test conducted within the body of a probe situated inside the screened portion of a well. Unlike other methods, IWPVPs channel groundwater flow as it passes through a well, magnifying the speed of the water through the probe and decreasing the time needed to conduct a measurement (Figure 3.1). The viability of the IWPVP method was demonstrated in laboratory experiments and with numerical modeling of the device. However, that work was based on a prototype IWPVP not designed for multiple deployments in the field. The purpose of this article is to (1) design a packing system to attach to the probe making it suitable for multiple field deployments and (2) to field test the IWPVP at a well characterized site to assess its utility and evaluate its performance.

3.3 Methods and Materials

The IWPVP operates on the principal that apparent tracer velocities measured within the screened portion of a well are proportional to the ambient groundwater velocity in the aquifer (Figure 3.1). Using a calibration line, generated in laboratory tank tests using representative aquifer material and a section of well screen with the same specifications as the field case, the magnitude of groundwater velocity in the field – including an approximate groundwater flow direction – can be estimated.

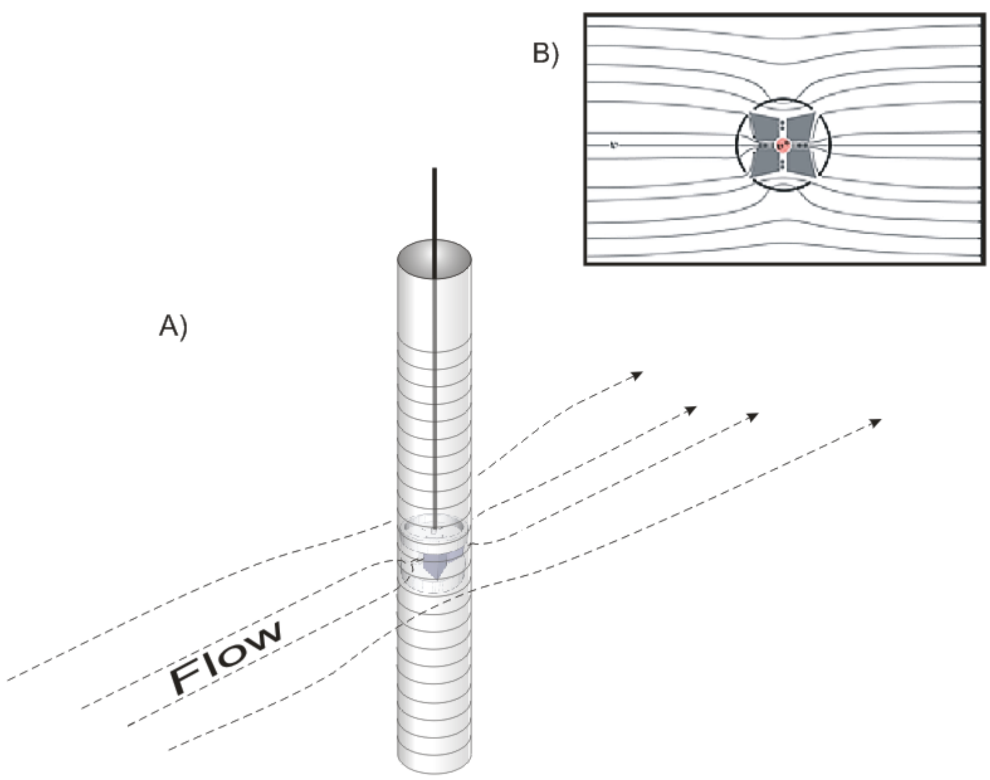

Figure 3.1. A) Schematic of horizontal flow through a well screen and an IWPVP. B) Plan view of flow through the IWPVP.

3.3.1 Field IWPVP Assembly

In order to create an IWPVP suitable for use in the field, the original prototype design (Figure 3.2a) was modified to support a brush packer system (Figure 3.2b). The concept of brush packers was based on the combined need to 1) permit quick repeatable deployments of the IWPVP, 2) establish barriers to flow between the inside of the well screen and the probe so water is directed through the tracer injection and detection system, 3) to accommodate the need for packers running both vertically and horizontally on the probe surface. Given that flow through the probe is open water (no porous medium), it was reasoned that directing the majority proportion of flow through the probe would not require perfect seals from the packer system, i.e., a metaphorical *aquitard* packer would suffice in place of the typical *aquiclude* packer for the purposes of this probe. The brush packer system consists of four custom half-circle bushes to discourage vertical borehole flow, and four custom straight brushes to discourage flow occurring around the IWPVP through the annular space. To accommodate the brush packer system, the field prototype was re-designed with a smaller outside diameter (O.D. = 4.9 cm) and an increased probe height (8.9 cm). The internal distances of the detection system were retained (tracer source to second detector wire = 1.06 cm). For deployment purposes, the field IWPVP design also incorporated a rod linkage assembly. The linkage assembly connects 1.27 cm O.D. (0.5 inch) PVC pipe to the body of the IWPVP for the purposes of pushing the probe into place and recovering it after use. The rod is also used to track the geographic orientation of the probe (Figure 3.2b). The field IWPVP was designed using Trimble SketchUp®, 3D printed with ABS (Acrylonitrile Butadiene Styrene) plastic, and assembled as described in Chapter 2.0.

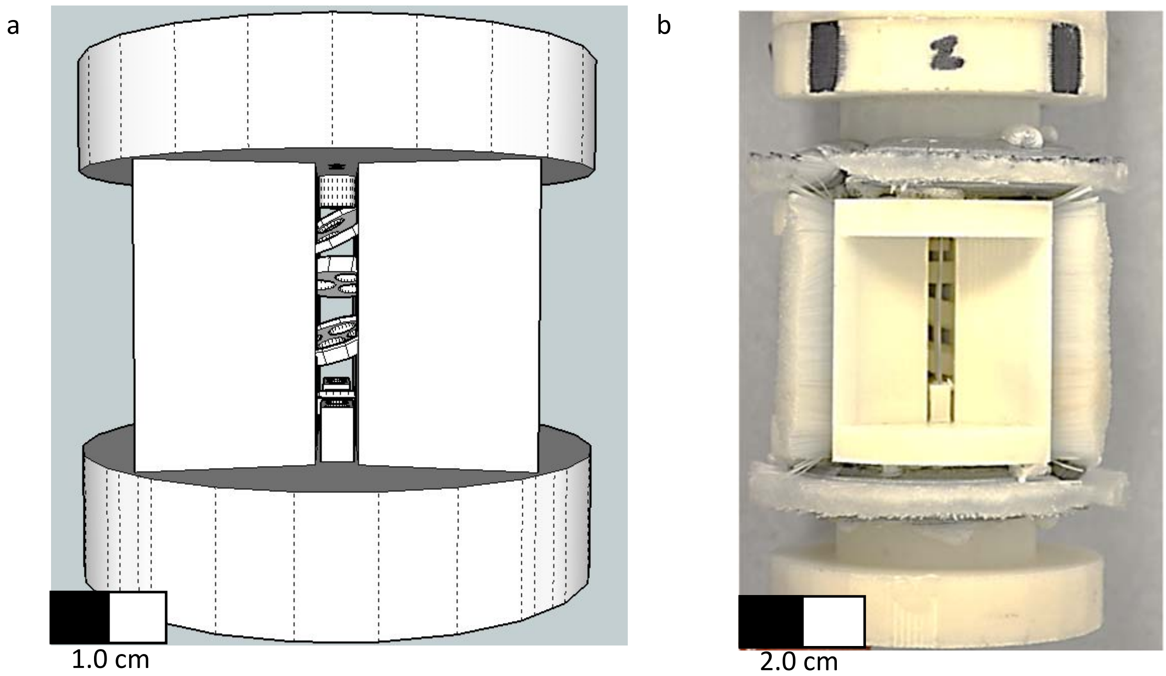

Figure 3.2. Design schematics illustrating the changes made between (a) the original IWPVP prototype, and (b) the fully assembled field IWPVP with the custom brush packer system glued into the recessions of the probe.

3.3.2 Experimental Methods

To assess the viability of the brush packer system, the redesigned IWPVP was subjected to a series of laboratory experiments. All experimental tests were conducted in a nested storage tank aquifer simulator (NeST) as described by Bowen *et al*. (2012). The central sand compartment was packed with homogeneous medium-grained sand with an effective porosity of approximately 0.33, measured gravimetrically as described by Gibson and Devlin (in preparation). For comparison purposes, all experiments conducted in this study used the same schedule 40 PVC, 0.508 mm (0.020 in) slot width, 4 row well screen used in Chapter 2.0. Once the NeST was filled with water, the well screen was emplaced in the center of the NeST sand compartment with screen openings oriented directly up gradient and downgradient. Sand was then packed around the well screen, ensuring the well screen remained level throughout the packing, to a final depth of 25.5 cm (NeST cross-sectional area = 892.5 cm^2). The well screen was then developed by surging a minimum of six times using a smaller diameter PVC slug, ensuring good hydraulic connection with the porous medium. The field IWPVP was then pushed into the well screen with half-bridge (HB) 4 oriented upgradient. After installation of the field IWPVP, the water in the NeST was recirculated for a minimum of 2 hours before the start of testing, to ensure steady state flow. Recirculation rates ranged from 10 mL/min to 77mL/min, and were maintained using a peristaltic pump. Tests were initiated by injecting 0.1 mL of 500 mg/L NaCl solution through the top of the central chamber of the probe. The injections were administered over a 10 second interval using an automated syringe pump.

The average expected flow velocity, $v_{expected}$, through the sand was determined based on the recirculation rate of water from the downgradient tank to the upgradient tank as described in detail elsewhere and applying the formula,

$$v_{expected} = \frac{Q}{An} \tag{3.1}$$

where Q is the discharge rate (L^3T^{-1}), A is the cross-sectional area of the tank (L^2) and n is the effective porosity (dimensionless). Calibration lines were then generated by averaging four replicate measurements at each pumping rate and plotting the average measured velocities against the average expected velocities.

3.3.3 Study Site

Field experiments were carried out in an alluvial sand and gravel aquifer at the O'Rourke Bridge Site, on the Arkansas River in Pawnee County, Kansas (Butler *et al.,* 2004) (Figure 3.3). The alluvial aquifer is comprised of sand and gravel deposits with intermittent clay lenses throughout. Direct push electrical conductivity logging revealed the presence of a possible 1 m thick clay and silt aquitard within the shallow alluvial aquifer beginning at approximately 5 m below ground surface (bgs) (≈17 ft bgs), potentially dividing the alluvial aquifer into an upper and lower unit. The shallow alluvial aquifer is separated from the underlying High Plains aquifer by a clayey aquitard occurring approximately 10 m bgs (≈32 ft bgs) that varies in thickness across the site with no apparent pattern from 3.1 to 6.6 m (10.3 to 21.8 ft) (Figure 3.4). In the area of this study, near LWPH6, the best estimate of the alluvial aquifer thickness was 4.57 m (Butler *et al.*, 2004, table 1 see LWPH 1). The transmissivity of the alluvial aquifer sediments was estimated to be 353 m^2/day, leading to a preliminary estimate of the hydraulic conductivity of the alluvial aquifer of 77 m/day, consistent with slug tests performed in the upper portions of the alluvial aquifer (Butler *et al.*, 2004).

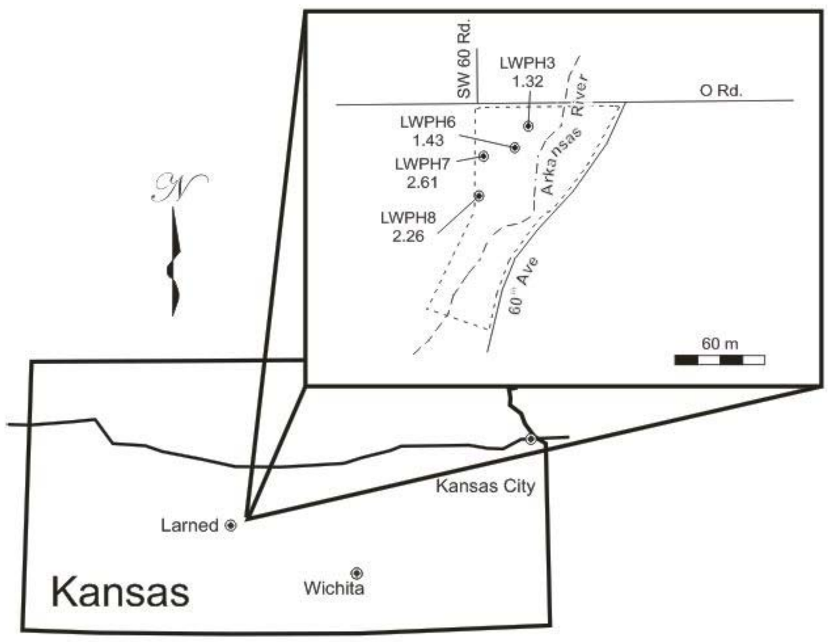

Figure 3.3*.* Location of the O'Rourke Bridge site.

All field testing in this study was completed in well LWPH6. The well was installed by the Kansas Geological Survey (KGS) in 2004 using a Geoprobe unit (66DT). The well was installed using direct push methods and is constructed from 6.35 cm O.D. (2 inch) flush joint casing with a 2.21 m, schedule 40, 0.508 mm (0.020 inch) slot width, 4 row screen. This well was selected because its construction was consistent with the well screen used in the NeST testing. The screened section of the well was isolated from the surface by plugging the annulus with bentonite. LWPH6 was developed by pumping 38 L/min (10 gallons/min) or greater, until groundwater turbidity was determined to be minimal as described by Butler *et al.* (2004). Since the development of LWPH6 following installation, no subsequent development was undertaken at the request of the KGS. At the time of this work, the well had partially been invaded by roots at the level of the water table.

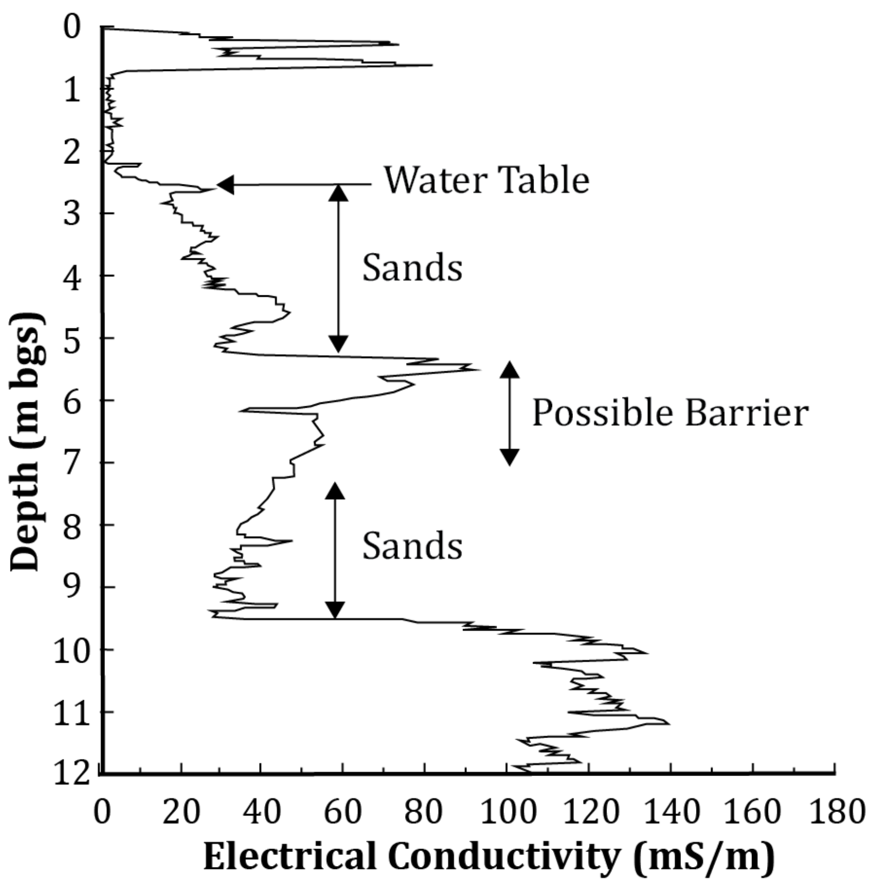

Figure 3.4. Electrical conductivity logging profile of the O'Rourke Bridge Site alluvial aquifer indicating the presence of a possible clay confining unit between approximately 5-6 m bgs (Modified from Butler et al., 2004).

3.3.4 IWPVP Field Methods

Prior to installation of the IWPVP, water levels from four monitoring wells located as shown in **Figure 3.3** were measured. The IWPVP was then installed in well LWPH6 by slowly pushing the probe downhole until the IWPVP was fully immersed in the groundwater. Immersion was indicated by declines in the normalized detector resistivity from 1.0 to about 0.5. An equilibration period of 1 hour was observed to allow the detector signals to stabilize before testing began.

Field testing was initiated by introducing a 0.1 mL pulse of 250 mg/L NaCl tracer solution over a 10 second time period with an automated syringe pump. This tracer strength was found to be sufficient to contrast with the total dissolved solids content of the ambient groundwater, providing good signal strength from the IWPVP. In an attempt to further increase the signal strength, testing was undertaken using an injection volume of 0.2 mL administered over a period of 40 seconds. Upon completion of each test, the observed electrical resistivity was allowed to return to baseline, before the initiation of the next test to ensure no residual tracer was present in the body of the probe. A test took roughly 10 minutes to complete. The signals recorded by the data logger were in millivolts that were proportional to the electrical resistivity of the solution in the detector channels. During data processing, these values were inverted to obtain data points proportional to electrical conductivity, lending the breakthrough curves to be easily modeled with solutions to the advection dispersion equation (Schillig, 2012).

3.4 Results

3.4.1 Laboratory Verification of Field IWPVP

The viability of the field IWPVP brush packer system was investigated by repeating the series of laboratory tank experiments used to evaluate the original IWPVP prototype. By duplicating the conditions as closely as possible, the effect of the brush packers on the probe performance could be evaluated. In the NeST tests with the original IWPVP prototype, linear calibration lines were produced for velocity ranges of about 50 cm/d to about 400 cm/d with slopes between 6.2 and 7.9, depending on subtleties in the packing of the sand in the tank (Figure 3.5). The slope of a calibration line for velocities ranging from 48 cm/day to 376 cm/day for a single tank packing and with the brush packers on the IWPVP was 8.4, in good agreement with the earlier tests (Figure 3.5). Furthermore, the standard deviation observed between quadruplicate tests performed with the field IWPVP was ± 6% compared to the ± 7% observed with the prototype IWPVP. These results indicate that the brush packer system performed to the same standard as was observed for the packers used on prototype probe, which achieved complete hydraulic separation of the detector channels from each other in the annular space outside the probe. This result justified taking the redesigned IWPVP to the field for further testing.

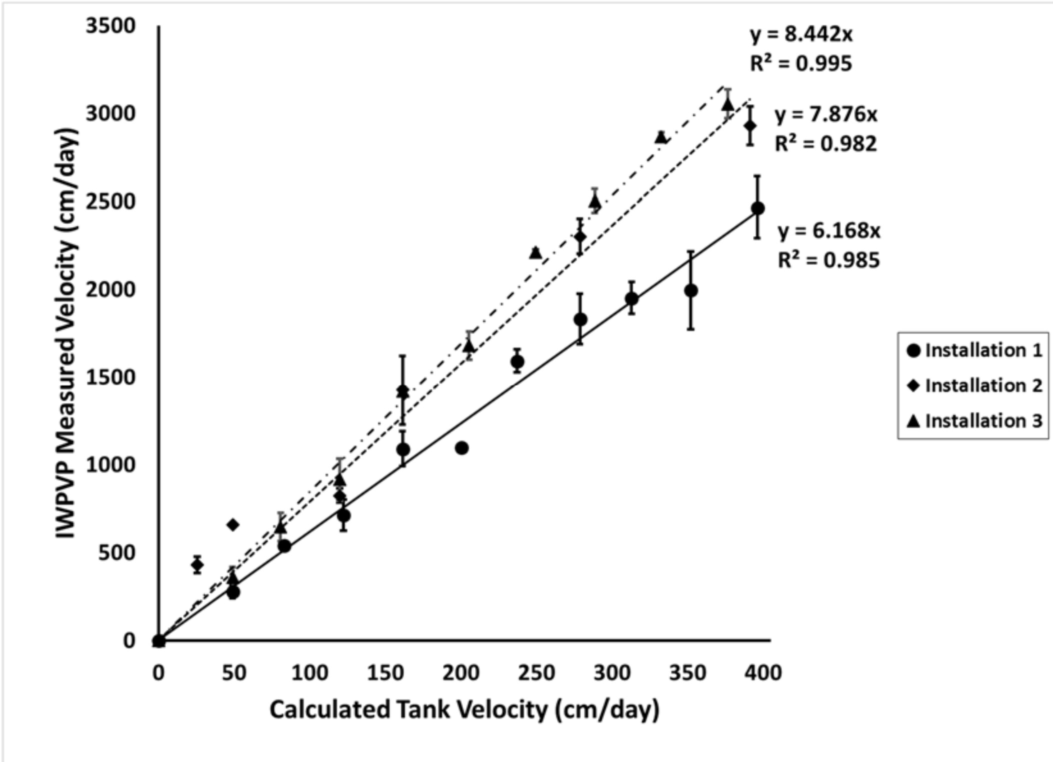

***Figure 3.5**.* Experimental calibration lines for the two prototype IWPVP installations (installation 1 and 2), and the field IWPVP installation (installation 3). The slight difference between the slopes of the calibration lines is thought to be related to differences in well-screen condition and tank packing. The error bars represent the first standard deviation of the quadruplicate tests.

3.4.2 Field Site Testing

3.4.3 Determination of groundwater velocity via Darcy's Law

A site-wide estimate of groundwater velocity based on a hydraulic gradient analysis, was conducted using HydroGeoEstimatorXL (Devlin, In Preparation). Water levels from the four monitoring wells shown in **Figure 3.3**, including LWPH6, were collected and used to estimate groundwater flow. On the basis of these water levels, HydrogeoEstimatorXL calculated a site-wide gradient of 0.0182 with water flowing 161^{o} from North (clockwise). HydrogeoEstimatorXL also calculates the gradient from every combination of well triplets, and in this case the average was 0.0196 ± 0.0014 (one standard deviation) with a flow direction of $160^{o} \pm 4^{o}$. Well LWPH6 was completed in the upper portion of the aquifer. Assuming the hydraulic conductivity of the alluvial aquifer was 77 m/d, as discussed in Section 3.3.3, and an effective porosity of 0.33, which is typical for sand and gravel, the Darcy calculation leads to an estimated groundwater velocity of:

$$v = -\frac{K}{n}\frac{\Delta H}{\Delta x} = -\left(\frac{77\frac{m}{d}}{0.33}\right)(0.0182) = 4.2\ m/d, \tag{3.2}$$

with groundwater flow towards the southeast at about 160° (**Figure 3.6**).

3.4.4 Field IWPVP Measurements

A total of 9 individual IWPVP tests were completed during the study, with the IWPVP installed in two orientations. In five tests the probe was orientation with HB4 approximately 15° east of magnetic north (20° east of true North) with the center of the probe located 2.1 m below the top of casing (btoc). Four additional tests were conducted with the probe orientated such that HB3 was approximately 15° east of magnetic north with the center of the probe located 2.09 m btoc. Six of the nine tests produced signals suitable to evaluate groundwater velocity. The two similar orientations were selected to evaluate the repeatability of IWPVP measurements between installations. Individual measurements of velocity inside the IWPVP ranged from 371 cm/day to 493 cm/day, with flow directions ranging from south-southwest to southeast (Figure 3.6; Table 3.1). Using the calibration line slope of 8.4 to convert from the probe measurement to an ambient groundwater velocity, IWPVP measurements produced a maximum estimated groundwater velocity of:

$$v_{groundwater} = \frac{v_{raw}}{8.2} = \frac{4.93\ m/d}{8.4} = 0.60\ m/d \tag{3.3}$$

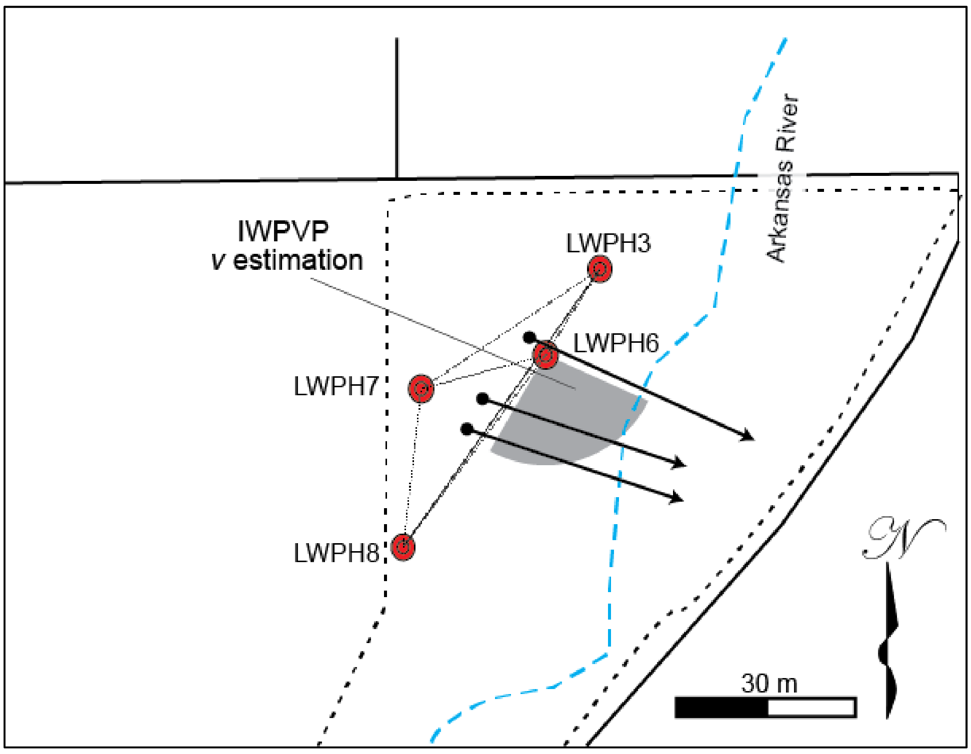

Figure 3.6. Map view of the O'Rourke Bridge site showing the locations of the piezometers (red filled double circles), the three point estimators (dashed triangles connecting well triplets) and the associated velocity vectors (the solid black arrows). The lengths of the velocity vectors are proportional to the water speed in the direction of groundwater flow, with the circle end of the velocity vector representing the estimator centroid. Also shown is the range of flow directions indicated by the IWPVP measurements, with radius of the shaded region proportional to the measured water speed in the aquifer, using the flow in gravel calibration curve.

The IWPVP-measured velocities indicated flow was occurring to the southeast, on average, in general agreement with the Darcy's Law predictions. The IWPVP is only designed to provide quadrant-level measurements of flow direction, though more refined estimates may be possible in some cases. Therefore, the level of agreement experienced in these tests is considered reasonable.

The magnitude of the groundwater velocity from the IWPVP was about 7 times lower than the Darcy-based estimate of velocity. This difference may simply be attributable to errors in the assumed values of K and $n_{effective}$. However other factors may also account for the difference. For example, interferences in the well, caused by root mats that had penetrated the screen may have restricted flow through the well and hence through the probe. The root mat growth also prevented IWPVP installation deeper than 2.1 m btoc, introducing potential measurement bias due to the close proximity to the water table. Another possibility is that the IWPVP responds differently when deployed in different aquifer media. This might occur because of permeability differences between the aquifer material and the detector channels in the probe. Less permeable aquifer material, such as sand, may promote a greater degree of flow focusing to the well and higher velocities measured by the probe, compared to more highly permeable sediments, such as gravel. Thus, an IWPVP calibration line might be expected to be steeper for a probe in sandy material than one in a gravel medium.

Table 3.1. Summary of analyzed IWPVP field measurements converted to estimated aquifer velocities.

Test #	**Orientation**	**Injection Volume (mL)**	**Injection Length (sec)**	**IWPVP Measured Apparent Velocity (m/day)**	**Estimated Aquifer Velocity[1] (m/day)**	**Estimated Aquifer Velocity[2] (m/day)**
1	1	0.1	10	4.06	0.50	1.20
2	1	0.1	10	4.09	0.50	1.20
3	1	0.2	40	4.51	0.55	1.33
4	1	0.2	40	3.71	0.45	1.09
5	2	0.2	40	4.93	0.60	1.45
6	2	0.2	40	4.74	0.58	1.39

NOTES:

[1] Estimated aquifer velocities calculated using the slope of the sand calibration line.

[2] Estimated aquifer velocities calculated using the slope of the gravel calibration line.

The alluvial aquifer, with an estimated *K* of 77 m/d, could comprise considerable gravel, which would not be distinguishable from sand in the EC logs (Figure 3.4) (Schulmeister *et al.*, 2003). If gravel is present within the aquifer, a more suitable calibration line may be required to convert the raw IWPVP measured velocities to groundwater velocities. In attempt to quantify the effect of gravel on IWPVP calibration, the field IWPVP was subjected to a series of laboratory tests with the NeST packed with fine to medium gravel with a porosity of 0.4. Tests were again run in quadruplicate with tank velocities ranging from 65 cm/day to 290 cm/day. The resulting calibration line was found to have a slope of 3.4, a notable decline as anticipated from the discussion above (Figure 3.7). Applying this new calibration line slope to convert the raw IWPVP values to an estimate of groundwater velocity:

$$v_{groundwater} = \frac{v_{raw}}{3.4} = \frac{(3.71\ or\ 4.93)\ m/d}{3.4} = 1.1\ or\ 1.5\ m/d \tag{3.4}$$

(Table 3.1).

Accounting for the change in porous medium improved the agreement between the Darcy estimate of velocity and the IWPVP measurement, bringing the difference to within a factor of about 3. It seems likely that much of the remaining difference is related to 1) the condition of the well – causing a negative bias in the IWPVP measurements – and 2) uncertainty in *K*. Further work, preferably with wells in better condition, is required to complete the IWPVP evaluation more definitively.

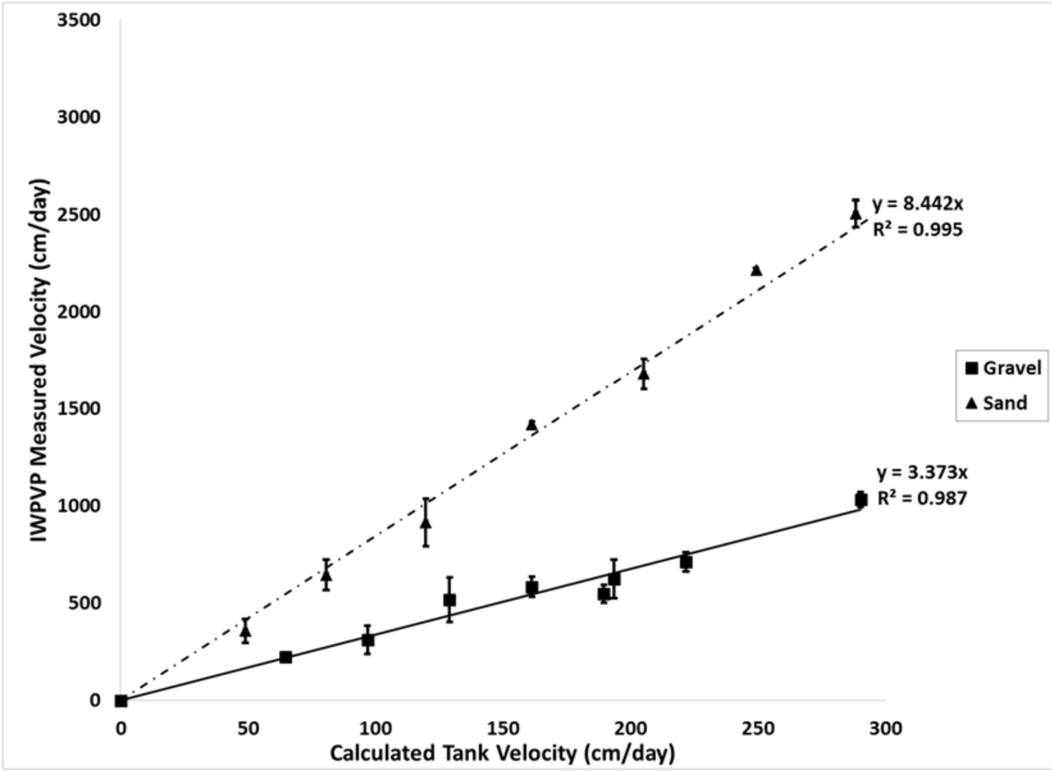

***Figure 3.7**.* Experimental calibration lines for the two different packing mediums, gravel (squares) and sand (triangles), with the error bars representing the first standard deviation of the quadruplicate tests.

3.5 Conclusions

It is concluded that the IWPVP can be outfitted with brush packers for quick and easy deployments of the probe in groundwater monitoring wells. The brush packers caused no decline in probe performance compared to packers that completely sealed the annular space between the probe and well screen.

In the field, the IWPVP was found to be a rapid and cost-effective tool for using existing groundwater monitoring wells to measure groundwater velocity. The tool was able to determine the general flow direction correctly. With further testing, more refined determinations of flow direction may be possible to obtain. In this study, the IWPVP estimated groundwater velocity to be a factor of 3 less than the Darcy's Law prediction. However, unambiguous imperfections in the well screen caused by root mat growth made a definitive assessment of the IWPVP difficult. Moreover, the Darcy-based estimated groundwater velocity utilized a hydraulic conductivity value calculated based on a transmissivity, which is an idealized site average and may not be representative of the portion of the aquifer near LWPH6.

Finally, individual IWPVP measurements from a narrow interval of a well screen should not be expected to compare perfectly well with larger scale Darcy estimations of velocity.

The strength of the IWPVP is its ability to rapidly and cheaply determine groundwater velocities, in a preliminary sense, at the centimeter-scale. This technology could be useful to identify sites or locations on sites where more detailed direct velocity measurements are warranted. The probes are relatively inexpensive and reusable, and the data collection requirements (datalogger, software) are identical to those required by the original PVPs (Devlin *et al.*, 2009).

3.6 References

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4.0 Conclusions and Recommendations

4.1 Conclusions

4.1.1 Numerical Modeling

Based on the results of the numerical model, the conceptual theory used to design the initial IWPVP is valid. The numerical model returned a linear calibration line of IWPVP measured velocities when simulated aquifer velocities ranged from 10 cm/day to 500 cm/day, indicating the quadrant IWPVP design was viable. Furthermore, the model showed that the IWPVP design was sensitive to various commercial well screen configurations, and provided a foundation for evaluating the initial experimental results.

4.1.2 Initial Prototype IWPVP

In a series of idealized laboratory tank tests, the prototype IWPVP produced a calibration line with a slope of 6.2 and a maximum standard deviation on groundwater speeds of ± 14%, when tank velocities ranges from 48 cm/day to 400 cm/day. Although the experimental calibration line did not exactly match the initial conceptual model results based on the numerical modeling, the initial conceptual model was found to have a positive bias due to the model's inability to account for well screen resistance. Once well screen resistance was taken into account, the slope of the experimental calibration line compared within ± 6% of the slope of the calibration line produced by the numerical conceptual model. Therefore, it is concluded that the difference between the theoretical and experimental behavior of the IWPVP is caused by the presence and condition of the well screen. Additional experiments completed in two independently packed tanks also indicated that IWPVP measurements are sensitive to the condition of the porous media surrounding the screen. For that reason, the IWPVP will not be able to be calibrated with porous medium that is identical to the field settings. These limitations are most likely true for all in-well techniques. As a result, it is important to understand the type and condition of the well screen in question and hydro-stratigraphy within the measurement interval.

By design the IWPVP has a limited ability to measure the directional component of groundwater velocity of 45°. It is concluded from this work that this design expectation was achieved.

In benchtop rotation testing, the prototype IWPVP was able to determine the groundwater speed in the NeST within ± 6%, on average, independent of the orientation of the IWPVP downhole. As a result, it is concluded that the IWPVP is able to accurately measure the groundwater speed, independent of the orientation, if the proportion of the open screen and the geometry of the probe are taken into account. The correction in these experiments was 1.4 for orientations where two breakthroughs occurred.

Based on initial numerical modeling and laboratory testing, it is concluded that the IWPVP has the ability to be an inexpensive tool to obtain groundwater velocity in groundwater wells.

4.1.3 Field IWPVP

On the basis of a series of laboratory tank experiments it is concluded that a brush packing system for the quick and easy deployment in groundwater monitoring wells.

In the field, the IWPVP was deployed in an undeveloped well with roots breaching the screen and found to measure a groundwater velocity 3 time less than that predicted by a Darcy's Law calculation. However, the Darcy-based estimation utilized a site-wide hydraulic conductivity value which may not be representative of the portion of the aquifer near the monitoring well. Furthermore, the imperfect nature of the well screen tested made a conclusive assessment of the IWPVP difficult. Lastly, individual IWPVP measurements encompassing a 3 cm interval of a single well screen should not be expected to compare precisely to a site-wide Darcy-based groundwater velocity estimation due to the differences in the scales of the measurements. Still, the IWPVP was able to determine the general direction of groundwater flow correctly.

Overall, the IWPVP was found to be a rapid and cost-effective tool for the measurement of groundwater velocity within existing groundwater monitoring wells for use in both sand and gravel. Based on the initial field testing, it is concluded that the IWPVP is a tool capable of determining centimeter-scale groundwater velocities, in a preliminary sense, in a rapid and cheap manner. On this basis, the IWPVP appears to be a viable tool for use in conjunction with, or for verification of, other more traditional methods to obtain groundwater velocity measurements and identify sites or specific locations where more detailed direct velocity measurements are merited.

4.2 Recommendations

This research focused on the development of an in-well point velocity probe for use in well screens with and inside diameter (I.D.) of 5.08 cm (2 inches). IWPVPs of this type are desirable for determining centimeter-scale groundwater velocity using existing groundwater wells. Not all existing groundwater wells are completed to an I.D. of 5.08 cm. Further development and design testing is needed for the diversification of designs to allow the IWPVP to be used in all existing groundwater wells, regardless of the diameter. Similarly, this study only utilized one of many different commercially available well-screen designs. Again, to ensure an IWPVP can be used in all existing groundwater wells, further work is needed to determine the tools ability to accurately and repeatedly determine groundwater velocity within various well screen configurations and materials.

Another area that requires further investigation is the effect of channel width on the IWPVP's ability to measure groundwater velocity. This study utilized an IWPVP design with a channel width of 2.7 mm, in which produced a linear calibration line when tank velocities were between 48 cm/day and 400 cm/day. Depending on the aquifer material and the range of expected groundwater velocity occurring at particular sites, site-specific IWPVP designs could potentially increase the accuracy of measured velocities.

Lastly, this study was focused on the initial design testing and verification of a tool for the measurement of horizontal groundwater velocity within commercial well screens completed in unconsolidated material. Using this work as a foundation, future work could be focused on adapting the IWPVP to include: (1) the ability to measure horizontal groundwater velocities in slow flow environments such as silt and clays, (2) the ability to detect vertical groundwater velocity, when present, and (3) the ability to be used in any open borehole completed in consolidated material.